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Theoretical Study of 1-Methoxy-2-sulfanylethan-1-yl Cation: Insight into Intermediates in Glycosidation Reactions

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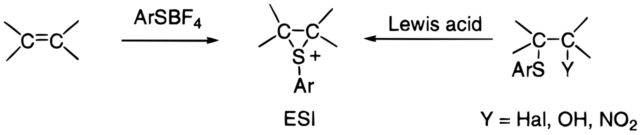
Equilibrium structures and harmonic vibrational frequencies of two model compounds related to the intermediates of nucleophilic attack on 1-alkoxy-2-(arylsulfanyl)alkyl halides and 2-(arylsulfanyl)pyranosyl halides are reported. Hartree−Fock (HF) and second-order Møller−Plesset (MP2) calculations using the 6-31G(d) basis set were performed on the larger of the two model ions, 2-sulfanyltetrahydropyran-1-yl cation. The smaller model ion, 1-methoxy-2-sulfanylethan-1-yl cation, was further investigated with a triple split valence, 6-311G(d,p), basis set and with the quadratic configuration interaction, including single- and double-electron excitations (QCISD), method. Localized atomic charges in the model ions were compared to corresponding sites in oxonium and episulfonium. The studies of the model ions suggest that the intermediate is more like an oxonium ion than an episulfonium ion, although the sulfur is critical to the stereoselectivity. High-level calculations (QCISD(T)/- and CCSD(T)/6-311++G(d,p)) indicate that a previously unidentified proton-shifted second intermediate, located 8.0−8.5 kcal/mol higher in energy, may be involved in reaction mechanisms. The unimolecular transition state corresponding to this proton shift was found to be 27−29 kcal/mol above the 1-methoxy-2-sulfanylethan-1-yl cation.

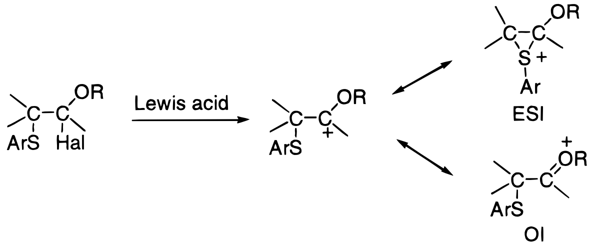
Introduction

Episulfonium ions[1] (ESIs) are three-membered sulfur-containing cationic species that have been postulated as intermediates in many reactions, including electrophilic addition of ArSCl to alkenes[1a,b] and reactions of various nucleophiles with *β*-(arylsulfanyl)-substituted alkyl halides,[1c] alcohols,[2] and nitro compounds[3] (Scheme 1). Although there is some doubt in the involvement of ESIs in the reaction of ArSCl with olefins under conditions of moderate polarity,[1a,b] the formation of these intermediates in the reactions of *β*-(arylsulfanyl)alkyl halides with nucleophiles is generally accepted.

Scheme 1



Scheme 2



Mechanisms of the reactions of 1-alkoxy-2-(arylsulfanyl)alkyl halides (or alcohols) and 2-(arylsulfanyl)pyranosyl halides (or pyranosides) with different nucleophiles in the presence of a Lewis acid appear to be more complex because of the possibility of forming either ESIs or oxonium ions (OIs) as intermediates (Scheme 2). The involvement of the ESI in these reactions has been generally accepted;[4] however, interconversion of the ESI and OI has also been proposed.[4k−n] There are some experimental data that suggest the direct attack of a nucleophile on the ESI. For example, the exclusive formation of the products with trans configuration of the ArS group and a newly introduced substituent at C(1) supports the ESI mechanism of the reactions (Scheme 3).[1,4] In contrast to the ESI reaction pathway, the direct attack of a nucleophile on the OI derived from pyranosyl chlorides (without the ArS substituent at C(2)) leads to the preferential formation of an α-glycoside, regardless

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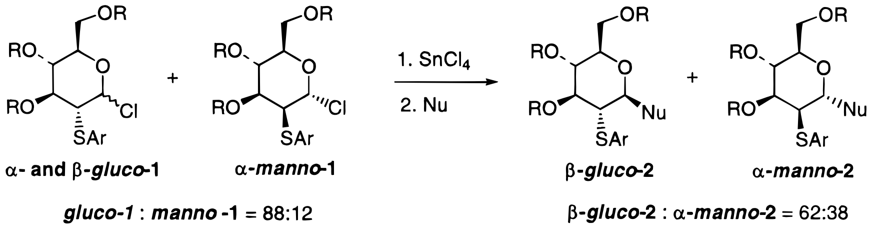
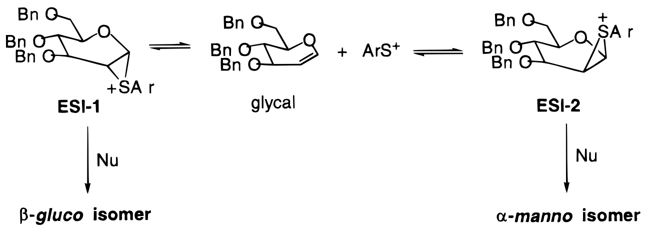
Scheme 3



Scheme 4



of the configuration at C(2). The stereochemistry of this reaction is explained by the anomeric effect.[5] It has also been observed that, in the presence of a Lewis acid and in a solution of CH_3NO_2, the reaction of a 88:12 mixture of 3,4,6-tri-*O*-benzyl-2-(arylsulfanyl)-2-deoxy-D-glucopyranosyl and the corresponding mannopyranosyl chlorides (**1**) with a carbon nucleophile provides a 62:38 mixture of 3,4,6-tri-*O*-benzyl-2-(arylsulfanyl)-2-deoxy-*β*-glucopyranosides and the corresponding α-*C*-mannopyranoside (**2**, Scheme 3).[4b] Such an epimerization at C(2) cannot be explained using the OI mechanism. It was suggested that there is an equilibrium between two forms of the episulfonium intermediate in the latter reaction.[4b] However, it is not clear how the interconversion of the two forms of the ESI occurs. One possible mechanism of the interconversion is the formation of a glycal and ArS^+ (Scheme 4). However, the glycal can react with a nucleophile itself, but none of the products of the latter reaction have been found.[6] It indicates that, if indeed the interconversion takes place, it occurs faster than the reaction of the glycal with the nucleophile.

Thus, experimental data obtained in the reactions of O- and C-nucleophiles with 2-(arylsulfanyl)pyranosyl halides and related compounds show that the ArS group affects significantly the stereoselectivity of glycosidation and supports the ESI mechanism. However, the single published theoretical study suggests that OI is more stable than ESI.[7] Few theoretical studies on alkylated carbonyl OIs[8,9,10] have been reported, and we were unable to locate any for OIs containing sulfur, other than the aforementioned study performed at the MNDO semiempirical level. Furthermore, few calculations on ESIs[11,12] have been reported. The lack of data and the unresolved contradiction between extant theoretical work and experimental evidence necessitates further study. Theoretical studies may also provide insight into the electronic structure of such ions, which may be difficult to obtain directly from experimental results, but may be valuable in understanding their reactivity. In this paper, we report the results of ab initio calculations on model ions related to intermediates of glycosidation reactions. Each ion (**3**, Figure 1 and **4**, Figure 2) contains the basic S−C−C−O−C backbone that is of primary interest, while **3** is comprised of an actual pyranose ring. Derivatives of **4** in which the substituent on the sulfur was changed have also been calculated and are reported herein. In an effort to offer a possible explanation of the epimerization at C(2) mentioned previously, the equilibrium geometry, vibrational frequencies, and relative energy of a third ion (**5**, Figure 3) were calculated. The unimolecular transition state connecting **4** and **5** was also calculated. Better understanding of ions **4** and **5**, along with the transition state, may give insight into the question of the nature of the intermediate in glycosidation reactions.

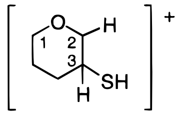


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Figure 1. 3-Sulfanyltetrahydropyran-2-yl cation.

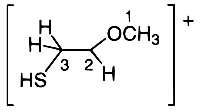

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Figure 2. 1-Methoxy-2-sulfanylethan-1-yl cation.

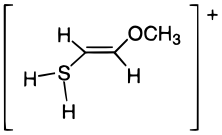

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Figure 3. Proton-shifted isomer of **4**.

Computational Methods

All calculations in this study were performed using the Gaussian94 Revision E.2[13] suite of programs, running under UNIX 4.0 on a DEC Alpha 500/400 workstation; unless noted otherwise, default settings for Gaussian94 Revision E.2 were

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Table 1. Geometrical Parameters of 3 and 4 at HF and MP2 Levels of Theory with 6-31G(d) Basis Set[a]

	$S-C_3$	C_3-C_2	C_2-O	$O-C_1$	$S-C_3-C_2$	C_3-C_2-O	C_2-O-C_1	$S-C_3-C_2-O$	$C_3-C_2-O-C_1$
3 (HF)	1.840	1.482	1.235	1.490	103.0	125.0	124.5	113.3	10.1
4 (HF)	1.839	1.477	1.236	1.466	103.0	127.2	125.7	96.0	2.5
3 (MP2)	1.848	1.466	1.274	1.504	94.5	124.9	121.5	106.9	6.1
4 (MP2)	1.845	1.462	1.275	1.476	92.8	127.6	121.9	96.6	1.9
4 (QCISD)	1.849	1.472	1.271	1.479	97.3	127.4	122.4	95.3	2.8

[a] Bond lengths in angstroms, bond and torsion angles in degrees.

Table 2. Comparison of 6-31G(d) and 6-311G(d,p) Basis Sets and MP2 (FC) versus MP2 (Full) on Geometrical Parameters of 4[a]

MP2	$S-C_3$	C_3-C_2	C_2-O	$O-C_1$	$S-C_3-C_2$	C_3-C_2-O	C_2-O-C_1	$S-C_3-C_2-O$	$C_3-C_2-O-C_1$
6-31G* (FC)	1.845	1.462	1.275	1.476	92.8	127.6	121.9	96.6	1.9
6-31G* (full)	1.843	1.460	1.274	1.473	92.5	127.6	121.9	96.5	1.6
6-311G** (FC)	1.846	1.462	1.270	1.466	91.1	127.9	120.9	98.2	1.7
6-311G** (full)	1.844	1.460	1.269	1.463	90.8	127.9	120.9	98.3	1.5

[a] Bond lengths in angstroms, bond and torsion angles in degrees.

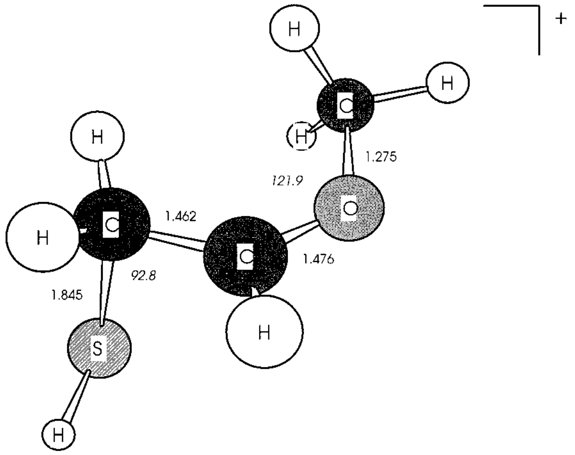

Figure 4. MP2/6-31G(d) geometry of **4**. Bond lengths in angstroms, bond angles in degrees.

used for basis sets and convergence criterion. Geometry optimizations were performed at the Hartree–Fock and MP2 levels of theory for **3** and at the HF, MP2, and QCISD[14] levels of theory for **4**. Table 1 lists some geometrical parameters of **3** and **4** calculated using the above-mentioned methods with the 6-31G(d) basis set. A comparison of basis set effects and effects of correlating the core electrons was also performed. Table 2 lists the geometrical parameters of **4** at the MP2 level of theory, using both the 6-31G(d) and 6-311G(d,p) basis sets. It also includes data from geometry optimizations involving correlation of all electrons and correlation of only valence electrons, denoted as FC. Figure 4 shows the optimized structure of **4**, from the MP2/6-31G(d) level calculation.

It may be seen from Table 1 that ions **3** and **4**, which both have the S–C–C–O–C backbone, have quite similar geometrical parameters: bond lengths, bond angles, and torsion angles. The only notable difference between **3** and **4** is the shortening of the $O-C_1$ bond length in **4** (0.028 Å at the MP2 level). On the basis of this observation, further calculations were performed on **4**, since it is thought to represent accurately the most important features of **3** and larger molecules but is much less computationally demanding.

In comparisons using a higher level of theory for geometry optimizations of **4**, i.e., QCISD vs MP2, we corroborate the standard assumption that the MP2 level of theory is sufficient in obtaining a reliable geometry for closed shell systems. However, it should be noted that the effect of higher levels of correlation is not entirely negligible but is perhaps not large enough to warrant larger calculations: only one bond length, the single carbon–carbon bond, changed noticeably (0.01 Å). The effect of increasing the basis set on the predicted equilibrium geometry was also considered. It may be concluded that the effect of adding polarization functions to hydrogen and using a triple split instead of a double split valence basis does not significantly change the geometry. In almost all cases, the bond lengths changed less than 1/100 Å and the bond angles less than 1.5°. Thus, these first set of calculations justify the argument that the geometries obtained at the MP2(FC)/6-31G(d) level are sufficiently accurate.

To more accurately determine energy differences between **4** and **5**, high-level ab initio methods (MP4, QCISD including triple excitations[16] and CCSD including triple excitations[14,17]) were used with both the 6-311G(d,p) and 6-311++G(d,p) basis sets at the MP2(FC)/6-31G(d) geometries. Diffuse basis functions were added to properly describe the charge density on electronegative atoms in the relative energy studies.

Vibrational frequencies were obtained at the MP2(FC)/6-31G(d) level for **4** and **5**. For purposes of further comparison of **4** with **3**, vibrational frequencies of **3** at the HF/6-31G(d) minimum were calculated at the HF/6-31G(d) level. Zero-point vibrational energy corrections are included in the comparison of energies between **4** and **5**.

The transition state corresponding to the proton shift from **4** to **5** was optimized at the MP2(FC)/6-31G(d) level. MP2 vibrational frequencies were obtained for this structure as well. In this case, the presence of one imaginary frequency, corresponding to a vibrational mode involving the proton that was shifting, used to verify the structure as the correct transition state. As with structures **4** and **5**, MP4, QCISD, and CCSD energies, including triple excitations, were calculated for this transition state using the 6-311++G(d,p) basis set. Zero-point vibrational energy corrections were included in the determination of the transition-state barrier.

To develop a qualitative understanding of the chemistry of the ions under study, it was of interest to examine the local atomic charges. Mulliken charges were obtained at the MP2 level for structures **4**, **5**, and for a model ESI (**6**, Figure 5) and

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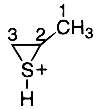

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Figure 5. Episulfonium ion.

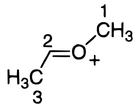

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Figure 6. Oxonium ion.

Table 3. Geometrical Parameters of 6 at HF and MP2 Levels of Theory, Using the 6-31G(d) Basis Set[a]

	$S-C_3$	$S-C_2$	C_3-C_2	$S-C_3-C_2$	$S-C_2-C_3$	$S-C_3-C_2-C_1$
HF	1.863	1.915	1.451	69.3	65.5	−104.8
MP2	1.854	1.886	1.465	68.1	65.8	−105.6

[a] Bond lengths in angstroms, bond and torsion angles in degrees.

Table 4. Geometrical Parameters of 7 at HF and MP2 Levels of Theory, Using the 6-31G(d) Basis Set[a]

	C_3-C_2	C_2-O	$O-C_1$	C_3-C_2-O	C_2-O-C_1	$C_3-C_2-O-C_1$
HF	1.473	1.231	1.468	120.9	124.1	180.0
MP2	1.462	1.260	1.488	120.1	121.4	180.0

[a] Bond lengths in angstroms, bond and torsion angles in degrees.

model OI (**7**, Figure 6); when possible, Gaussian94's implementation of Atoms in Molecules,[15] or AIM, was also used.

Results

To describe **4** as being similar to an OI or ESI, it was necessary to compare **4** to an actual OI and ESI of similar composition. Figure 5 shows the reference structure for the ESI, while Figure 6 shows the reference structure for the OI. Tables 3 and 4 list some of the geometrical parameters of **6** and **7**, respectively, as optimized using HF and MP2 levels of theory with the 6-31G(d) basis set. The geometrical structures of these two ions are not unusual, but the localized charges (vide infra) do not appear to be as straightforward as the geometrical parameters.

On the basis of the comparison of the data presented in Tables 1, 3, and 4, it appears that the geometries of both **3** and **4** have many characteristics similar to an OI. Efforts to find a second stationary point, whose geometry resembled that of an ESI, were unsuccessful. One carbon−oxygen bond length, that of the C_1-O bond, is significantly longer than the other, even though each bond length is slightly larger than the respective average carbon−oxygen single and double bonds. The bond angle between the sulfur and the two carbon atoms is around 90°, which is much larger than one would expect for an ESI, which may be expected to be around 70° (see Table 3). A few of the harmonic vibrational frequencies, along with their intensities, of compounds **3**, **4**, **6**, and **7** are given in Table 5. The vibrational frequencies also support OI character. The most intensely absorbing normal mode is in the characteristic region for a carbonyl stretch, while the stretching modes for the hydrogens are above 3000 cm^{-1}. So, ab initio calculations on model ions **3** and **4** support the earlier semiempirical calculations[7] on larger compounds that these types of cationic species tend to be OIs.

The effect of replacing the substituent on sulfur was considered next. Table 6 lists the geometrical parameters of **4** with the hydrogen on the sulfur being replaced by chlorine and by a methyl group. From the data in Table 6, it is apparent that the effect of the methyl group is noteworthy from a geometrical standpoint; the angle between the sulfur and the carbons becomes smaller upon replacement of the hydrogen with the methyl group. The angle still appears to be too large for this to be considered an ESI, but this decrease is large in comparison to the change upon replacement by chlorine. The shorter of the carbon−oxygen bonds, i.e., the C_2-O bond, is lengthened significantly, while the other carbon−oxygen bond is shortened. Both of these phenomena allow for the possibility that when the hydrogen on the sulfur would be replaced by a larger alkyl or aryl group, such as the ones discussed in the Introduction, the structure may be even more episulfonium-like. Thus, semiempirical calculations on substituted structures, giving no ESI-like character, ought to be reexamined.

A planar intermediate may be the cause of the epimerization of the carbon attached to the ArS group in glycosidation reactions. One possible intermediate is that of the type represented by ion **5**, which occurs with a proton shift from C_3 to the sulfur in **4** forming a carbon−carbon double bond. A plot of the HOMO of this ion shows significant carbon−carbon π-bond character, as can be seen in Figure 7. Ion **5** therefore has the geometrical structure needed to support such an interconversion of the sulfur. Table 7 lists the relative energy of **5** with respect to **4** at various levels of theory and basis sets. From these data, it appears that the adiabatic energy difference between these two isomers is between 8 and 8.5 kcal/mol. It should be noted that the calculations reported herein are of ions in the gas phase; solutions of these ions may have energy differences that are larger or smaller.

The structure of the unimolecular transition state corresponding to the proton shift from **4** to **5** is given in Figure 8. The relative energy differences between this transition state and compounds **4** and **5** are given in Table 8. Zero-point vibrational energy corrections are included in the reported values. Table 9 includes some of the harmonic vibrational frequencies for structures **5** and the reported transition state. A full listing of vibrational frequencies for all reported molecules is included in the Supporting Information.

Discussion

Calculations reported above support an OI-like structure for the 1-methoxy-2-sulfanylethan-1-yl cation; the question of the role of the sulfur remains to be addressed. Figure 9 shows that the major contribution to the HOMO of **4** comes from diffuse atomic orbitals around the sulfur, e.g., a lone pair. The directionality of this orbital and its diffuse nature suggest that a nucleophile will attack **4** predominantly from the opposite face than that of the sulfur. In the case of these types of ions, one would expect a great majority of the products to have the trans configuration. Experimentally, it has been shown that such stereoselectivity does exist for nucleophilic attack upon ions of this nature.[1,4]

Table 5. Selected Harmonic Vibrational Frequencies (cm^{-1}) of 4, 6, and 7 at the MP2/6-31G(d) Level[a]

	3	4	6	7
C_3-S stretch	691.4 (0.4)	706.4 (1.5)	631.7 (9.9)	
C_1-O stretch	809.0 (58.7)	876.6 (46.1)		851.5 (64.6)
C_2-O stretch	1816.8 (378.8)	1664.1 (362.4)		1723.6 (200.0)
C_2-H stretch	3393.0 (2.6)	3247.2 (4.0)	3229.9 (3.7)	3186.6 (0.2)
C_2-C_3 stretch	974.9 (7.3)	959.8 (7.6)	1257.1 (1.1)	1010.6 (9.7)

[a] Harmonic vibrational frequencies of **3** are at the HF/6-31G(d) level. Intensities are in parentheses.

Table 6. Effect of Substitution at Sulfur on the Geometry of 4[a]

X	$S-C_3$	C_3-C_2	C_2-O	$O-C_1$	$S-C_3-C_2$	$X-S-C_3$	$S-C_3-C_2-O$	$X-S-C_3-C_2$
H	1.845	1.462	1.275	1.476	92.8	112.0	96.6	88.3
Cl	1.842	1.463	1.273	1.478	93.8	100.0	101.7	88.3
CH_3	1.842	1.457	1.301	1.460	80.3	101.2	103.5	95.4

[a] Calculations performed at the MP2/6-31G(d) level. Bond lengths in angstroms, bond and torsion angles in degrees.

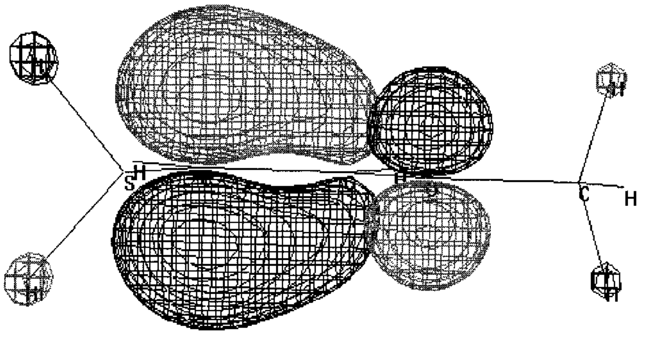

Figure 7. Molecular orbital plot of HOMO of **5**.

Table 7. Relative Energy of 5 with Respect to 4 Using MP2/6-31G(d) Optimized Geometries[a]

	6-311G(d,p)	6-311++G(d,p)
MP4(SDQ)	8.0	8.4
MP4	8.6	8.8
QCISD	8.3	8.6
QCISD(T)	8.4	8.7
CCSD	7.8	8.1
CCSD(T)	8.3	8.5

[a] Energies are in kcal/mol.

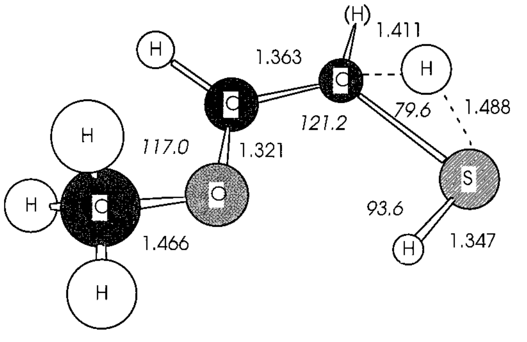

Figure 8. MP2/6-31G(d) geometry of transition state between **4** and **5**. Bond lengths in angstroms, bond angles in degrees.

Table 8. Activation Energies Relative to 4 and 5 Using MP2/6-31G(d)-Optimized Geometries[a]

	4	5
MP4(SDQ)	37.6	29.3
MP4(SDQT)	35.2	26.4
QCISD	38.0	29.4
QCISD(T)	35.8	27.1
CCSD	37.7	29.6
CCSD(T)	35.8	27.2

[a] All energy calculations were performed using the 6-311++G(d,p) basis set. Energies are in kcal/mol.

Table 9. Selected Harmonic Vibrational Frequencies (cm^{-1}) of 5 and the Transition State at the MP2/6-31G(d) Level[a]

	5	transition state
C_3-S stretch	779.9 (4.0)	657.7 (25.6)
C_1-O stretch	1029.5 (80.0)	1014.7 (16.1)
C_2-O stretch	1345.5 (231.4)	1342.1 (176.4)
C_2-H stretch	3215.0 (8.1)	3219.4 (17.2)
C_2-C_3 stretch	1726.5 (279.9)	1684.5 (243.0)

[a] Intensities are included in the parentheses.

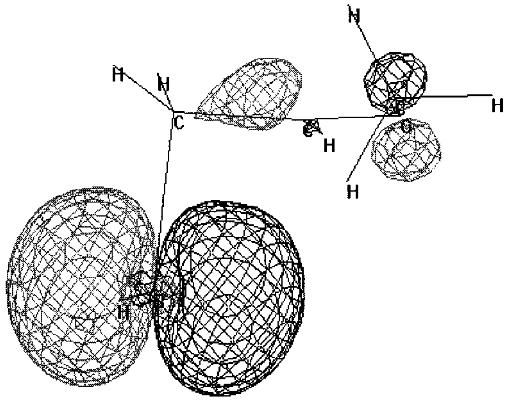

Figure 9. Molecular orbital plot of HOMO of **4**.

Previous calculations[10] have been reported on OIs involving the pyranose ring without the sulfur. Table 10 is a listing of the geometrical parameters of **3** and of the bare pyranose ring cation. These data shows that the geometrical parameters of **3** are essentially independent of the sulfur substitution, since the carbon−oxygen bonds differ only by 0.01 Å and the valence angle by 0.3°. This observation supports the idea presented in the preceding paragraph that the role of the sulfur group in this chemistry is its ability to direct the stereochemistry of the reaction by sterics and/or electrostatics and not by directly affecting the geometry of the intermediate.

To qualitatively understand the problem of epimerization of the carbon attached to the ArS group in glycosidation reactions, we propose the following hypothesis. Before nucleophilic attack occurs at the α-carbon, an equilibrium between **4** and **5** may exist. Once the planar structure **5** forms, if the barrier to rotation about the S−C bond is not too high, it is possible that the exchange of the proton back to the carbon (to reform **4)** may occur on the opposite face as did the exchange to form **5**. If this were the case for a ring structure, the position of the

Table 10. Effect of Sulfur on Bond Length and Angles of Oxonium Ions Involving Pyranose Ring[a]

oxonium ion	C_1-O	C_2-O	C_1-O-C_2
pyranose[b]	1.514	1.261	121.8
3	1.504	1.274	121.5

[a] Geometrical parameters calculated at MP2/6-31G(d) level. Bond lengths in angstroms, bond angles in degrees. [b] From ref 10.

Table 11. Localized Charges of Heavy Atoms in 6

	Mulliken[a]	AIM[a]
C_1	0.197	0.247
C_2	0.036	0.078
C_3	0.160	0.213
S	0.607	0.463

[a] Charges of hydrogens are summed into heavy atoms.

Table 12. Localized Charges of Heavy Atoms in 7

	Mulliken[a]	AIM[a]
C_1	0.489	0.709
O	−0.271	−1.113
C_2	0.559	1.045
C_3	0.214	0.358

[a] Charges of hydrogens are summed into heavy atoms.

sulfur would then shift from axial to equatorial position or vice versa. Although the gas-phase energy difference of 8.0−8.5 kcal/mol implies that the equilibrium is so one-sided that the proposed mechanism is not tenable, the difference is small enough that differential stabilization in solution may make the proposed mechanism plausible. The transition state barrier height is of interest in assessing the feasibility of the proposed mechanism. From the data presented in Table 8, it appears that the height of this transition-state barrier is around 36−38 kcal/mol relative to **4** and around 27−29 kcal/mol relative to **5**. Although the gas-phase barrier is far from being thermally accessible, it is sufficiently small to warrant further consideration for reactions in the solution phase. It is interesting to note that the structure of this transition state resembles that of **5**, where all of the heavy atoms are essentially in one plane. The dipole moments of structures **4**, **5**, and the transition state may give some insight as to the solution-phase reactivity. These values are 2.3, 3.5, and 1.2 D, respectively.

Tables 11 and 12 list the localized charges of the atoms of the model ESI ion, **6**, and of the model OI ion, **7**, respectively. According to Table 11, the charge distribution of **6** is as one would expect, with a large positive charge located on the sulfur atom. Ion **7**, however, is contrary to simple expectations. According to the usual representation of **7**, the oxygen atom ought to have a net positive charge, but according to calculations, the oxygen is actually carrying a fairly large negative charge. Since Mulliken populations are sensitive to basis set, AIM calculations, which are more nearly independent of basis set, were used to give a better indication of the actual charges. In the case of the AIM calculation, the oxygen carries more than a whole negative charge. The nucleophilic carbon atom carries a large positive charge, which is also nearly a whole charge according to the AIM calculation. This calculation also predicts that all three molecular orbitals corresponding to carbon−oxygen bonds have 70% ionic character.[18] Therefore, the view of an OI (**7**) as having a positively charged oxygen may not be an accurate description of its electronic structure.

Table 13. Localized Charges of Heavy Atoms in Model Ion 4

	Mulliken[a]
C_1	0.459
O	−0.304
C_2	0.516
C_3	0.021
S	0.308

[a] Charges of hydrogens are summed into heavy atoms.

With reference to the above calculations on **6** and **7**, the charge distribution in the model ion can now be described. Table 13 contains the Mulliken charges of the heavy atoms of **4**. The Gaussian94 AIM calculation on the model ion **4** did not converge. The data in Table 13 show that the nucleophilic carbon is still relatively positive, while the oxygen is still largely negative. It also shows that the sulfur is much less positive than in the case of **6**. On the basis of a comparison of Mulliken charges to AIM charges for **6** and **7**, one would expect that **4** has a much larger charge separation than is predicted by the Mulliken charges and that the charge on the sulfur is not nearly as positive as one would expect for an ESI. Another indication of this large charge separation between the nucleophilic carbon and the oxygen is the intensity of the harmonic frequency corresponding to the vibrational mode dominated by the carbon−oxygen stretch. Our calculation of the harmonic frequencies, and their intensities, of formaldehyde at the same level of theory and basis set (1212 [2.6], 1296 [10.0], 1583 [5.2], 1788 [58.1], 3013 [50.8], and 3085 [138.0]) predicts that the intensity of this carbon−oxygen stretch in **4** is about six times as large as that in formaldehyde (i.e., 362.4 vs 58.1). The vibrational data support the interpretation that the carbon−oxygen double bond in **4** should not be viewed as a traditional σ and π bond having partial positive charge on oxygen, but rather as having significantly greater charge separation.

Conclusions

The calculations presented in this paper indicate an OI structure for cations with an S−C−C−O−C backbone and hydrogen on the sulfur. However, in the case of substitution of alkyl groups on the sulfur, there may be a significant change in the geometry, although for methyl, the ion is still significantly more OI-like than ESI-like. To better understand the glycosidation reactions involving substrates with an arylsulfanyl substituent, the consideration of larger model ions may be necessary. In the case of the ions in this study, it is apparent that the sulfur plays a very minor role in the geometry of each ion.

For the ions in this study, the role of sulfur appears to be that of directing the stereochemistry sterically and electrostatically, in this case forming trans products upon nucleophilic attack. We propose that an ion similar to **5** offers a possible explanation into the cause of the observed racemization of the carbon attached to the ArS group in glycosidation reactions. The zero-point corrected energy of **5** is calculated to be only about 8.0−8.5 kcal/mol above that of **4**. The transition state involving this proton transfer has an activation energy of 27−29 kcal/mol above the less stable isomer (**5**). However, it must

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(18) Cioslowski, J.; Mixon, S. T. *J. Am. Chem. Soc.* **1991**, *113*, 4142.

be emphasized that these molecules were considered in gas-phase studies, and the effect of solvents on these relative energies are not known.

Our calculations on atomic charges suggest that the standard view of the electronic structure of an OI is perhaps not accurate. Data show that not only may the partial charges be contrary to the standard view but also the carbon−oxygen bonds in these structures may not be “classical” σ and π bonds.

Our calculations support the use of MP2(FC)/6-31G-(d) as a computationally suitable level for obtaining geometries of the ions studied. The effects of increasing the basis set and of increasing the accuracy of the treatment of dynamic electron correlation for such ions appears to be sufficiently small to not warrant the larger calculations.

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Supporting Information Available: Tables of optimized geometries and of harmonic vibrational frequencies and intensities for **3**−**7** and the transition state connecting **4** and **5**. This material is available free of charge via the Internet at http://pubs.acs.org.

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